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Abstract

The broad-scale circulation and dynamics of the magnetosphere is discussed in relation to some problems of the ionosphere. The importance of electric fields and charge separations in the production of various localized features of the magnetosphere seems assured. Many of the features discussed may be instructively interpreted in terms of the Chapman and Ferraro theory.

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I. Introduction

For more than half a century, ionospheric research of importance to radio has been closely linked to that of importance to geomagnetism. As early as 1883, Balfour Stewart[1] suggested that ionized regions of the upper atmosphere might be the site of upper air winds blowing to produce varying electric currents, causing changes with time in the geomagnetic field. The possibility that more than one ionized region might be involved arose in the course of the further development of Stewart's dynamo theory of the geomagnetic variations.[2] The cause of the ionized regions was thought to be wave radiation. In addition, contributions of solar charged particles to the ionization at levels near 100 km was discussed by Birkeland[3] in his studies of the auroral-zone electric currents causing geomagnetic bays. He found that these electric currents must, on occasion, exceed 1,000,000 amperes, and hence require considerable flow of ionized particles within the atmosphere. He also undertook experiments in which he propelled electrons within an evacuated chamber in the presence of a small magnetized _terrella_ simulating the earth magnet. These experiments provided photographs of illuminated features at ionospheric levels of the _terrella_ and of ring currents at higher levels furnishing graphic aids of inspirational importance to theoretical workers in geomagnetism and aeronomy over the 60-year period which followed. The concepts introduced by Birkeland, though based upon experiments in plasma physics, were discussed in terms of particle physics; actually the fluid concept of plasma physics had not yet been brought forward, though flow of electrical and magnetic energy as effluvia down geomagnetic field lines had been postulated in rudimentary form as early as 1693, in the writings of Halley and others discussing the aurora. It is therefore clear that some early studies in geomagnetism provided fundamental contributions to ionospheric research. Since geomagnetic time variations arise from varying currents flowing in the ionosphere, and are dynamic manifestations of the ionosphere in motion, measurements of the geomagnetic variations supplement the information obtained from ionospheric soundings. Of course, our main knowledge has come from the exploration of the ionosphere by means of radio waves, propagated both upwards from the ground and downward from earth satellites moving above. Ions have also been measured directly by rocket borne instruments.

It will be the aim of the present study to summarize and amplify the discussion of a few selected aspects of geomagnetism which seem to contribute to our understanding of the ionosphere. Note is first taken of the solar streams of Chapman and Ferraro[4] or of these superposed in time and space yielding a solar wind.[5,6] The interaction of the stream with the magnetosphere is next discussed, with special attention to charged particle distributions along the nighttime boundary of the magnetosphere. Contributions of shock waves to the energy of the particles in the magnetosphere is also very briefly noted following Dessler, Hanson and Parker,[7] Kern,[8] Kellogg,[9] and others. The precipitation of particles into high latitudes to produce radio blackouts discussed by Wells,[10] Agy,[11] Hakura,[12] Matsushita,[13] and others, is considered together with the auroral and electrojet theories of Martyn,[14] Nagata,[15] Fukushima,[16] Kern,[17] Fejer,[18] and Swift.[19]

Associated motion of the ionosphere, especially the F-region, is noted along with pulsations in field and conjugate-point phenomena. Finally, F-region effects on magnetically quiet days will be noted with particular reference to the studies of Ratcliffe,[20] Hirono and Maeda,[21] and others; included will be some summarizing remarks on dynamo theories of the E-region. I also wish to comment briefly on an early study now requiring some correction and revision, in which the writer considered the possibility that the dynamo theory or fluid mechanics of the magnetosphere might give rise to magnetic disturbances.[22] Separation of charge by ionospheric motions such as zonal winds was discussed, as was consequent generation of electric fields and accelerations of particles in the polar ionosphere.

It was also suggested that hydromagnetic waves might be propagated within solar streams from sun to earth, arriving eventually at ground level. I also propose to discuss the hydromagnetic treatment of Axford and Hines.[23]

II. Geomagnetic and Ionospheric Disturbances Associated with Solar Streams

It is well known that disturbances at ionospheric levels, such as magnetic crochets and solar radio blackouts are often successfully linked to solar flares.[24] It is also well known that other ionospheric disturbances and geomagnetic and auroral effects are linked with active solar areas, often at intervals of a day or so following a solar flare, and therefore at a time interval allowing particles of only a few hundred electron volts to travel from sun to earth. During great solar flares, protons and other particles with energies approaching tens of billions of electron volts are known to arrive at ionospheric levels. These produce polar radio blackouts which appear a number of days each year. On occasion, particles presumably of solar origin have penetrated to ground level, even at the equator, where the energy requirements for penetration are extreme. These spectacular effects of high-energy particles, though very interesting, contribute a much smaller total energy than do the large numbers of lower energy particles impinging within the ionosphere. The latter are thought of as having acquired solar energy in some manner not yet understood. Until recently they mainly were thought of as arriving directly from the sun, but since their energy flux when measured within the terrestrial atmosphere exceeds that expected based on the results of space probes above the magnetosphere, a terrestrial (magnetospheric) enhancement of their energy seems necessary. Particles such as those observed over some months on Mariner II, in flight to Venus are compatible with a travel time of about a day from sun to earth, resembling (though not in detail) the solar outflows postulated long ago by Chapman and Ferraro.[4]

III. The Chapman-Ferraro Theory

Figure 1 shows an idealized solar-stream configuration in which particles of a few tens of electron volts are imagined by Chapman and Ferraro. The particles in the stream move radially outwards from the sun, and successive faces of the stream are shown. The interaction with the magnetosphere is shown in Fig. 2. On the sunward and afternoon side the geomagnetic field and its contents are compressed and the solar stream passes by on either side. It was suggested that particles might enter the magnetosphere on the day side at two singular points, one in high northern and the other in high southern latitudes. Actually, their figure shows particles on the night side, so distributed that an eastward directed electric field there, crossed with the upward directed field lines of the terrestrial dipole (at the equator) would drive particles towards the earth, and into the magnetosphere and radiation belts. We shall return to consider this result in some detail later, in connection with the new results of Explorer XIV for the nighttime magnetosphere.

Since some magnetic disturbances measured at ground level appear daily, streams of varying density and particle energies are probable. Thus, many solar streams like that of Chapman and Ferraro might be superposed, though the process of superposition would of course probably be more or less nonlinear, even for the initial phase of a storm that they worked out analytically. This circumstance has been discussed by Parker,(5) Obayashi,(25) Elliott,(26) Rossi,(27) and others, though without much analytical detail because of the inherent difficulty of the problem. A substantial advance in information, confirming many details of the foregoing discussion was afforded by the Mariner II observations between the Earth and Venus reported by Neugebauer and Snyder,(28) extending also the information on fields obtained aboard Explorer X.(29) Figure 3 shows a quiet-day pattern of magnetic field lines for a 300 km/sec solar wind.(30) As in the stream geometry of Fig. 1, the corresponding field carried by the stream becomes somewhat spiral — a consequence of the 27-day solar rotation. If we add the shaded section A, which we regard as including a denser stream of similar speed, as it overtakes the earth each 27 days, it will increase compression on the magnetosphere, within which may appear disturbances likely to resemble each other in some respect every 27 days. This of course leads to recurrence tendencies for ionospheric storms, geomagnetic disturbances, and aurora at roughly 27-day intervals. A possible simple 27-day recurrence of this type near sunspot minimum is shown in Fig. 4, for six solar rotations from September 1943 to February, 1944.[31] The large pulse enduring about one hour near midnight, if assumed associated with a density increase such as for A of Fig. 3 would imply a highly persistent and stable feature of the solar-wind — a narrow filament. The advancing face of A at the earth will move with an angular velocity depending on the rate of solar rotation, and the distance r from the sun. If the filamant A passes beyond the earth within an hour (neglecting time constants of effect due to the stream filament) in order to explain the effect we can estimate a cross section d of the filament A. Taking the solar rotation period to be 27 days = 324 hours, $d = (1/324); 2\pi \times 1.5 \times 10^7 \text{ km} \sim 3 \times 10^7 \text{ km}$. This small filament thickness d of only 300,000 km is comparable with that of a mean free path of the interplanetary medium, so that preservation of such a filament would require a remarkably stable magnetic field configuration within the stream, possibly weaker than that in adjacent regions. Since for a given cross section the energy of the field and particles is $W = B^2/8\pi + 1/2\ nmv^2$, where B is the magnetic field, n the number density, m the particle mass, and v the streaming velocity, an increase in n near the sun should be accompanied by a reduction in B. A local shock front increasing the transverse component of v may also include an electric field E, entering into the energy equations.

Actually, it is well to consider the known high-energy particles associated with great solar flares, which seem actually to have come from very near the sun. Their arrival near the earth seems often associated with a Forbush decrease in cosmic rays. Though it is not yet certain how this decrease is brought about, it seems necessary to associate a distortion of interplanetary clouds and field in order to explain the effect.[26,32]

IV. Magnetosphere Boundary

The calculations of Chapman and Ferraro relating to the boundary of the magnetosphere have been extended by various workers, using various simplifying assumptions. Figures 5 and 6 show results based on calculations of Spreiter and Briggs[33] and of Zhigulev and Romishevskii[34] for a dipole earth inclined to a solar stream. Another less detailed version is that of Ferraro,[35] shown in Fig. 7. It will serve for illustrative purposes here, in reporting some recent discussions of boundary phenomena, particularly those of my colleagues, Kern and Kahle.

Consider the distribution of charge near the boundary of Fig. 7. It arises, according to the Chapman-Ferraro theory of 1933, from the electric field there given by $\underline{E} = - \underline{v} \times \underline{B}$, where $\underline{v}$ is the velocity of the solar stream and $\underline{B}$ the local magnetic field. Consequently $\underline{E}$ depends more upon the velocity of the solar stream than upon the stream density deforming the field and the subsequent redistribution of charge ensuing over the boundary. The velocity component $\underline{v}$ tangential to the magnetospheric boundary engenders a polarization electric field arising from displacement of protons relative to electrons, across the tail of the earth. Chapman and Ferraro also showed that this effect is to be expected under widely different conditions of non-uniformity in field and velocity, though more recently they have considered that deeper penetration by protons than for electrons is expected on the day side. Accordingly, in the equatorial plane, they found in their earlier studies that positive charge may predominate on the morning near the dawn and early-morning-meridian half planes, and negative charges near the sunset and evening-meridian half planes. If we regard this arrangement as a huge parallel plate condenser, its capacity C is about 0.088 ϵ A/d in mmf, where ϵ is the dielectric constant, A the plate area and d the distance between the plates. The value ϵ varies over wide limits, since it is given by $\epsilon = 1 + \frac{4\pi Nmc^2}{B^2}$ where N is the number density of protons or electrons, m the mass density of a plasma, and B the magnetic field. Taking ϵ as very roughly about 10^3, A as 20 earth radii squared, and d as 20 earth radii, we have

$C \sim 0.88 \times 10^3 \times 20 \times 6.4 \times 10^8 = 1.1 \times 10^{12}$ mmf, or about one farad. The electric field lines will be normal to those of the geomagnetic field. They will be roughly perpendicular to the tail of the earth at great distances from the earth on the night side. Closer to the earth at the magnetospheric boundary, they will be nearly normal directed from dawn to evening sides; but they will curve earthward so that they are nearly parallel to the surface of the earth near midnight, in order to maintain the configuration orthogonal to the field, with flux determined by the dielectric constant. Hence, the electric field lines will be more numerous in nighttime magnetospheric regions with diminution in B, or in ionized layers of high N and consequent increase in dielectric constant.

The electric charge distribution shown tentatively in Fig. 2, which requires some revision near noon, will affect charged particles within the magnetosphere. If correct, this configuration may possibly also influence the equatorial electrojet on the day side, and the distribution of charged particles in the tail of the earth.

Figure 8 shows recent results of Frank, Van Allen, and Macagno[36] on the number densities of electrons of energy greater than 40 kev observed on Explorer XII and Explorer XIV. It would be expected that the contours of equal flux density would be stream lines along equipotentials. There is a dearth of particles beyond about 8 earth-radii along the central axis of the tail, in the absence of particle sources, since the force on both particles is in the direction $\underline{E} \times \underline{B}$, and $\underline{B}$[37] is likely to be such as to give an earthward velocity E/B. Actually, the transverse acceleration of particles may be roughly evB/mc, so that as the particles are driven earthward they are also accelerated. It is estimated that particles of low energy will be directed earthward along trajectories reaching the earth, whereas higher-energy particles may be driven only part of the way earthward, and more nearly transverse to the tail of the earth's field. Dr. Kern has pointed out to me that if these views are correct, perhaps in correspondence with Fig. 8, the hatched contours in evening should be asymmetrically disposed relative to the central axis of the nighttime cavity, an interesting prediction subject to experimental check. The particles might eventually encircle the earth in response to magnetic gradient drift, with continued acceleration by the electric field, which would be smaller tangentially to drift orbits near noon than at midnight. It seems necessary to suppose that, as has been often done before, somehow these particles cross the magnetospheric boundary from the solar stream, perhaps due to plasma ripples arising far out along the boundary tail.[15] The important Helmholtz instability of a plasma moving in contact with a parallel magnetic field was considered by Northrup,[38] who showed that growing irregularities might occur. Dessler[39] has suggested that the sunward boundary of the magnetosphere is stable. Far out along the nighttime boundary, however, it seems likely that fluctuations in the solar stream should give rise to exponential growth of flutes at the boundary, much as in the case of auroral curtains and arcs discussed by Kern and Vestine.[40] The disrupted flutes and their electric fields would then carry a supply of charged particles into the magnetosphere, perhaps as plasmoids. Once inside they should stream inward along contours close to the boundary probably nearly parallel to the contours of equal number density shown in Fig. 8 by Van Allen and his colleagues. The resulting acceleration and migration of charge will contribute to the ionozation of the polar ionosphere, as has been remarked by Hines. Figure 9 also tends to strengthen the view that the original boundary-charge distribution of Chapman and Ferraro is supported by experiments on ion beams.[41]

Finally, the numbers δW_2 of Bartels, proportional to electrojet strength appears to show the required compatible effect with decrease in electrojet strength at times of greater storm intensity. This would be predicted on the basis of Baker and Martyn's theory of the equatorial electrojet, the effect arising due to reduction of the west-to-east current flow on the part of equatorial atmospheric charges initially separated by the action of middle-latitude atmospheric winds.[42]

It is interesting to estimate charge amounts for the boundary region of the magnetosphere in order that effects on the S_q electrojet may occur. Examination of Baker and Martyn's values suggest that an applied electric field of about 10^4 emu/cm may have perceptible effects. This requires a potential difference of $4\pi\sigma d/\epsilon$ across the "condenser" and the capacity per unit area will be $\epsilon/4\pi d$. The field between the plates is $4\pi\sigma/\epsilon = 10^4$/cm, or $\sigma = 1/4\pi \times 10^4 \epsilon \sim 10^6 c$, if $\epsilon = 1,000$, in esu. Hence, the equivalent surface charge density leading to the polarization will be $10^6 \times 1 \sim 3 \times 10^{-5}/cm^2$. This may be considered distributed over a considerable thickness of boundary. For instance the spiral radius of a proton is about 100 km when B is about 100γ (one gamma = 10^{-5} cgs unit). The polarization electric field could otherwise be provided by about 7×10^{-3} protons/cc in such a boundary region. The polarization electric field is $(1/2\pi c)\ \underline{v} \times \underline{B}$, or if $B = 10^{-3}$ emu and the tangential velocity $v = 10^8$, the field required is $10^5/2\pi$ emu or about 10^4 emu/cm as before.

The transverse acceleration of the electrons is evB/mc so that a polarization displacement δr will take place in a time δt given by $(\delta t)^2 = m/f\pi e^2 N$, where N is the number density of electrons and protons, m is the mass of an electron, and f is the fraction by which the field fails to balance the electromagnetic forces. This gives $\delta y = 3.5 \times 10^{-3}$ sec, or a very short time as Chapman and Ferraro have shown.

Particles of either sign and whatever their mass in the central region of the tail of the earth will be driven earthward with a velocity $V_E = E/B$. Although Cahill has found some change in direction of the earth's dipole field, from Explorer XIV observations, the magnitude is not too different at distances eight or more earth radii above the ground.(37) Thus if $E = 10^4$ emu, $B = 10^{-3}$, and we assume 40 kev particles, we have an electric drift of $V_E = \frac{E}{B} = 100$ km/sec under static conditions, in the direction $\underline{E} \times \underline{B}$. If E varies slowly with the time, a polarization drift $\underline{V}_p = (mc^2/eB^2)\ \dot{\underline{E}}$. If we imagine E to develop in 1000 sec, say, $\dot{\underline{E}} = 10$ emu/sec, and protons would drift locally with the speed $10/9580 \times 10^{-6} \sim 10^3$ cm/sec; or 10^{-2} km/sec and smaller for electrons. A curvature drift depending upon sign of particles is opposite in sign for electrons and protons and for a radius of curvature of field line of about 4×10^9 cm gives about 20 km/sec for protons (less for electrons). A magnetic-field gradient drift is about 40 km/sec, and the sign is opposite for protons and electrons. A drift due to gravity is very small — of order 10^{-5} km/sec, perhaps.

The magnetospheric protons and electrons therefore drift rapidly earthward if the electric field is maintained at a level as high as 10^4 emu/cm and the trajectories will show a sensible shift to the east of protons and of electrons, with a number of earth radii negotiated during a few hours.

V. Dynamics and Particle Acceleration in the Magnetosphere

Recent surveys of particles in space, such as Mariner II have failed to find sufficiently energetic particles in quantity required to produce the aurora, and possibly polar current systems of geomagnetic disturbances.[36] Since measurements were made en route to Venus, and therefore over much of the region near the earth's orbit, it seems necessary to build a magnetospheric supply of particles by accelerating a part of the existing charged particles of the exosphere, whether these are driven in from solar streams as low energy particles (a few kev) by the electric fields near the boundary of the magnetosphere, or otherwise. The alternative of accelerating particles by an atmospheric process is not new, and previous studies have been made in the hope of finding a workable mechanism.[17,43] It has, in fact, been suggested years ago that dynamo effects in the ionosphere might contribute electric fields of interest in this connection.[22,44] In recent years these atmospheric fluid-motion concepts have been greatly extended in considerably greater generality throughout the magnetosphere, assuming energizing to ensue under the influence of the impinging solar wind.[23] The generation of fluid motions by interaction of a solar stream with the magnetosphere as well as by hydrodynamic waves (shock waves) within solar streams flowing from sun to earth, and hence to ground level, had in fact been discussed by the writer in 1954 but left undeveloped,[22] as well as the hydromagnetic aspects of storms. This type of theory really emerged through the detailed studies by Dungey,[45] Piddington,[46] Parker,[47] Dessler and Parker,[48] Cole,[6] and, as has already been noted in the comprehensive statements of Axford and Hines,[23] in some degree stemming from a suggestion of Gold.[49] Even earlier, the fundamental concept of magnetic fields frozen into plasma seems to have arisen from storm theory in works of Ferraro, and later by Alfvén. Many of the various suggestions cannot readily be tested, using specific and detailed calculations as was done for the initial phase of storms by Chapman and Ferraro, because of extreme analytical difficulties. Accordingly, it appears likely that the major opportunities for clarification of the role of atmospheric processes in particle acceleration ensue from use of rocket, satellite and space-probe measurements of particle flux, field, and composition of the upper atmosphere and magnetosphere.

There have been recent interesting discussions on the acceleration of particles, using concepts of fluid mechanics. One of the more promising approaches is that of accelerating charged particles by shock waves.[7,8,49-51] There is today some uncertainty respecting the role of shock waves in producing more than the sudden commencement of storms, because the various space probes have not discovered sufficiently accentuated wave fronts of potential shock waves in the solar wind. However, production of the sudden commencement by shock waves remains cogent.[4,48-51]

The processes of acceleration actually operative are of considerable interest to radio workers, because particles are presumably dumped from above and into the ionosphere. According to Kern[17] the interaction of a solar stream with the magnetosphere may give rise to magnetic field gradients directed towards the tail of the earth, separating and dumping charges to give north-south or south-north electric fields in auroral regions. These drive the electrojets of bays, and produce frequent radio blackouts in high latitudes such as those described by Wells[10] and others. These points have been otherwise discussed by Fejer[18] and by Cole[6] in criticism of Piddington's series of papers on storms.

The resulting electric fields in the E-region of the northern hemisphere will necessarily have a conjugate pattern in the southern hemisphere. The driving emf's, whether north-south or otherwise, must act across a segment of the ionosphere as shown in the figure due to Fejer.[18] Hence, the electric driving forces producing conjugate electrojets are necessarily present at both auroral zones, a point noted previously by Kern and Vestine.[40] Since mirror-point heights usually differ above conjugate northern and southern points joined by a geomagnetic field line, aurora may appear at one station and not at its conjugate. In the same way, since particles may not penetrate down as far as the E-region, the electric conductivity in one hemisphere may be much less, so that a weak bay in one hemisphere may be accompanied by a strong bay in the other. In the same way, radio blackouts may appear strongly in the hemisphere where mirror points are low near the electrojet, and not at all in the other hemisphere where mirror-point heights are more elevated above ground level. This finding also supports the flux-tube notion of Axford and Hines, since outer reaches of a flux tube will more or less track with motion of conjugate bases of the tube.

Various suggestions have appeared suggesting that electric fields assist in loading particles anew into the Van Allen radiation belts, e.g., see Vestine[52] or Akasofu and Chapman.[51] In fact, in at least one theory of magnetic storms due to Alfvén,[53] it is shown that many details of magnetospheric phenomena can be explained by using electric fields. Alfvén imagined that motion of solar streams across the solar magnetic field gave rise to the requisite electric fields across the earth. In the foregoing discussion on the results of Explorer XIV, we also considered such an electric field, though recourse was made to the Chapman and Ferraro calculations on charge distributions at the magnetospheric boundary. Subject to the condition that the magnetic moment of the particle must be preserved, it is clear that particles will be driven into the radiation belts, possibly building up ring currents yielding the main phase of storms. Since the cross-section of entry of particles is large, an acceleration process as well as the energy of storms can possibly be attained.

VI. The Axford-Hines Circulation of the Magnetosphere

A few comments relating plasma flow to electric charges on the magnetosphere boundary seems appropriate in order to examine the degree of agreement with Axford and Hines. Since their fundamental equation is $\underline{E} + \underline{V} \times B = 0$, it is obvious that agreement in this sense is perfect. We can either talk of $\underline{E}$, or of $\underline{V} \times \underline{B}$, or $\underline{V}$ itself, in a hydromagnetic medium. After a little reflection it becomes apparent that this perfect agreement is academic, since the only quantity known in even its grosser aspects is the main-field dominated term $\underline{B}$, and as Fejer has remarked,[18] it may suffer distortion and hence accentuate the difficulty of developing a quantitative theory. It is also clear that the boundary conditions for the charge yielding $\underline{E}$ are highly uncertain. The charge distribution described seems likely to give a distribution of electrons resembling that of Van Allen and his colleagues. But the radiation belt distribution could, in principle arise from an infinite number of charge distributions. In the same way, the Axford and Hines circulation shown in Fig. 10 can possibly be adopted and a charge distribution at the magnetospheric boundary driving it inferred. This requires the treatment of the anisotropic dielectric, as well as the distribution of $\underline{B}$.

Perhaps the most useful approach is to imagine an oversimplified version of the problem, with positive charges driven forward from far along the tail of the earth. This gives a flow forward, as in the figure; but the return, unless outside the magnetosphere (which we are not allowing for the moment), is completely unspecified. It is also likely that moving clouds of charges or plasmoids will prove the more feasible transport yielding a circulation.

The adequacy of the approximation $\underline{E} + \underline{v} \times \underline{B} = 0$ also clearly depends upon boundary conditions, temperature of the ionized gas, and uniformity of the magnetic field and the dielectric. The field and dielectric are obviously non-uniform, but, even so, motions of large cross-section may be well approximated by the equation.

VII. Conjugate Point and Other Ionospheric Disturbance Phenomena

The time changes of the F-region and E-region during geomagnetic disturbance are of considerable interest in radio-physics, because of their importance in radio communications. It has only recently come to be realized that low energy electrons in the upper F-region are probably interchanged along geomagnetic field lines. This of course means equatorial anomalies in the F-region require interpretation in terms of conjugate point locations, a matter recently discussed in a critical review address by Ratcliffe.[20] A convenient chart of conjugate points given recently by Kern and Vestine[40] is found in the Appendix. This may explain some features of similarity as well as dissimilarity in correlations of northern and southern hemisphere stations with solar indices noted by Mariani[54] who uses noon values of f_oF_2 for two eleven-year periods, 1937-1947, and 1947-1957, especially for latitudes above 55^oN or S which show maxima in linear regression coefficients connecting number density in the F_2-region with solar parameters. There are also probably indications shown of a strong number-density dependence given by annual means of f_oF_2 for nearly conjugate equatorial stations north and south of the equator in the region 30N to 30S. Mariani attributes effects to dumping of radiation belt electrons of energies in excess of 40 kev of about 10^5 to $10^6/cm^2sec$ with energy fluxes 10^{-4} to 10^{-3} erg/cm^2 on the basis of estimates of low energy electron flux by O'Brien[55,56] and Krasovskii, et al.,[57] Mariani does not discuss mechanisms of dumping the particles. However, the lowering of mirror points due to compression of the magnetosphere is one of the simplest ways of so doing. This has been indicated previously by Vestine,[58] Chamberlain, Kern and Vestine,[59] and Vestine and Kern.[60] For 10 to 40 kev electrons, the longitudinal drift rate is slow compared with the speed of the motion between mirror points. Since the magnetic moment $\mu = (1/2)m\ v_1^2/B$, where m is the mass of the particle and v_1 its spiral velocity is practically constant for fields varying slowly in a space over several spiral periods, a change in B due to compression involves lowering of the mirror point, and hence dumping of particles. The particles will literally be squeezed out of the outer radiation belt whence they may have arrived due to the Chapman-Ferraro electric field across the tail of the earth, and into the proper latitudes. Of course, the lowering of mirror points due to field distortion may also be discussed, with similar results, using the second (or longitudinal) adiabatic invariant.[59]

The various phenomena involving dumping of particles discussed by Mariani,[54] may therefore be related to regular seasonal changes in the geomagnetic field shown in the accompanying figure, likely to be produced by seasonal and non-seasonal effects of the solar wind. Changes in the F-region of similar type have been derived.[61] An interesting analogous time variation may appear in whistlers.[62]

A number of conjugate-point effects involving rapid transient changes or pulsations in the geomagnetic field are associated with the appearance of ionospheric changes, or with the aurora. Thus, Harang[63] found regular magnetic pulsations of some minutes period accompanying radio signals returned from the ionosphere. It was early noted that pulsations of auroral illumination on occasion have the same period as geomagnetic pulsations. Vestine found intervals of 2-second pulsations by direct timing of an auroral display that lasted nearly an hour in 1933.[64] In recent years these effects have been explored extensively and it has been established that phenomena of this type appear at magnetically conjugate stations by Campbell and Leinbach,[65] Troitskaya, Alperovich, Melnikova, and Bulatova,[66] and by Campbell and Matsushita.[67] Geomagnetic pulsations in field noted by a magnetometer aboard Explorer X were also discussed by Ness, Skillman, Scearce, and Heppner,[68] and a number of writers have indicated hydromagnetic theories of such pulsations.[69,70]

Ionospheric effects have also been discussed using models of solar-cycle variations in the upper atmosphere.[71,72] There are also effects due to storms such as those observed by Jacchia[72] and Paetzold and Zschoerner.[73]

An extensive series of papers dealing with general aspects of ionospheric storms in the F-region has appeared.[74-85] These results will not be considered in detail here. There is, in general considerable temporal agreement between effects noted in the F-region and those in geomagnetic storms. Up to a height of about 200 km, the storm effects are less pronounced. In the F-region a thickening occurs on the first day of storm, and there is often loss of ionization later, perhaps due to ionospheric heating.

A recent review of some storm effects in the F-region has been given by Somayajulu.[85] He dealt especially with effects noted during three severe magnetic storms. An interesting feature was the noontime depression in true height of about 100 km at Washington, D. C., on the storm days as compared with quiet days; other changes are indicated in the accompanying figure. For 42 storms, Matsushita[83] studied average aspects of the electron density N, the total ion content per unit column, and the electron content below various heights of the ionosphere. He analysed these data according to storm time and SD variations at 8 stations. Electron-density profiles on both storm and magnetically-quiet days were plotted against height and latitude. For the SD, most of the results in middle latitudes seem explicable in terms of electric fields of polar electrojets, operating on the ionosphere in the presence of the geomagnetic field. For the storm-time variation, Matsushita found an apparent increase in ionization occuring above the maximum height of the F-region at the beginning of the main phase of a storm. He suggests that this ionization may diffuse down the magnetic field lines and, under influence of gravity and pressure gradients, to regions above adjacent low-latitude stations. In slightly higher latitudes, a rapid decay process associated with temperature increase in the upper F-region in summer may occur.[20,84]

It would be interesting to examine geophysical results predicted by the theoretical Chapman-Ferraro distribution of charge on the magnetospheric boundary. Table 1 gives average effects noted in noon departures from the average in virtual height $\Delta h'F2$, and in critical frequency $\Delta f^{o}F2$ at Huancayo, for a series of storms or disturbances of the years 1938-1946. The magnetic character figure C_p ranges from 1.2 to 2.2. Apparently, virtual height lowers, and critical frequency increases. The corresponding change is shown in the daily magnetic variation S_q, as measured by the usual wave-radiation index W_2 of Bartels. The effects increase with storm intensity.

The bodily change in motion could be determined more informatively from incoherent scatter results, preferably near local noon, but it appears that the results of Table 1 are all compatible with a smaller electric field directed from west to east on storm days. A reduced field would reduce the lifting action on the F_2-region and increase the critical frequency. Since the Chapman-Ferraro electric field would be similarly directed, it may interfere with the equatorward migration of charge generated by meridional S_q winds in middle latitudes, thus reducing S_q and, of course, implying less effect on the F-region. There may also be other effects, such as lifting action on the E-region, affecting conductivity. On this basis therefore, the storm electric field, if it exists, would be appreciable, but presumably always less than the electric field producing the equatorial electrojet.

There might also be an effect on the polar-cap distribution of S_q electric currents shown in the accompanying figure, though the high anisotropic dielectric constant of the ionosphere renders estimates difficult in this case.

The final figure, showing variations in phase height of 16 kc/sec waves, has been discussed by Ratcliffe and Weekes.[84] The effects shown have been interpreted in terms of change in D-region height. The figure also seems to show that during storms and during the after field of storms there are nighttime changes that seem of special interest in connection with ionospheric and magnetic storms.

Table 1

(A) Departures in equatorial ionospheric noontime F-region parameters from monthly means with increase in magnetic planetary character-figure C_p, years 1938—46; also (B) departures normalized for change in sunspot number*

C_p	Number of storms	(A) $\Delta h'F2$	(A) Δf^oF2	(A) ΔW_2	(B) $\Delta h'F2$	(B) Δf^oF2	(B) ΔW_2
1.2	132	-7.2 km	+0.23 Mc/s	-5.3	-2.1	+2.8	-7.4
1.3	84	-8.7	0.29	-3.9	-2.6	3.2	-6.5
1.4	85	-5.9	0.29	-8.4	-1.7	3.7	-10.3
1.5, 1.6	98	-6.5	0.50	-7.9	-1.9	5.3	-9.9
1.7, 1.8	44	-12.8	0.57	-14.0	-2.8	5.7	-16.3
1.9, 2.0, 2.1, 2.2	27	-14.6	0.91	-25.6	-3.3	10.3	-25.2

*Values of (A) x 100 divided (1) by annual means of all days for $\Delta h'F2$ and Δf^oF2 and (2) for ΔW_2, by annual means for noon minus midnight in magnetic intensity H at Huancayo in gammas.

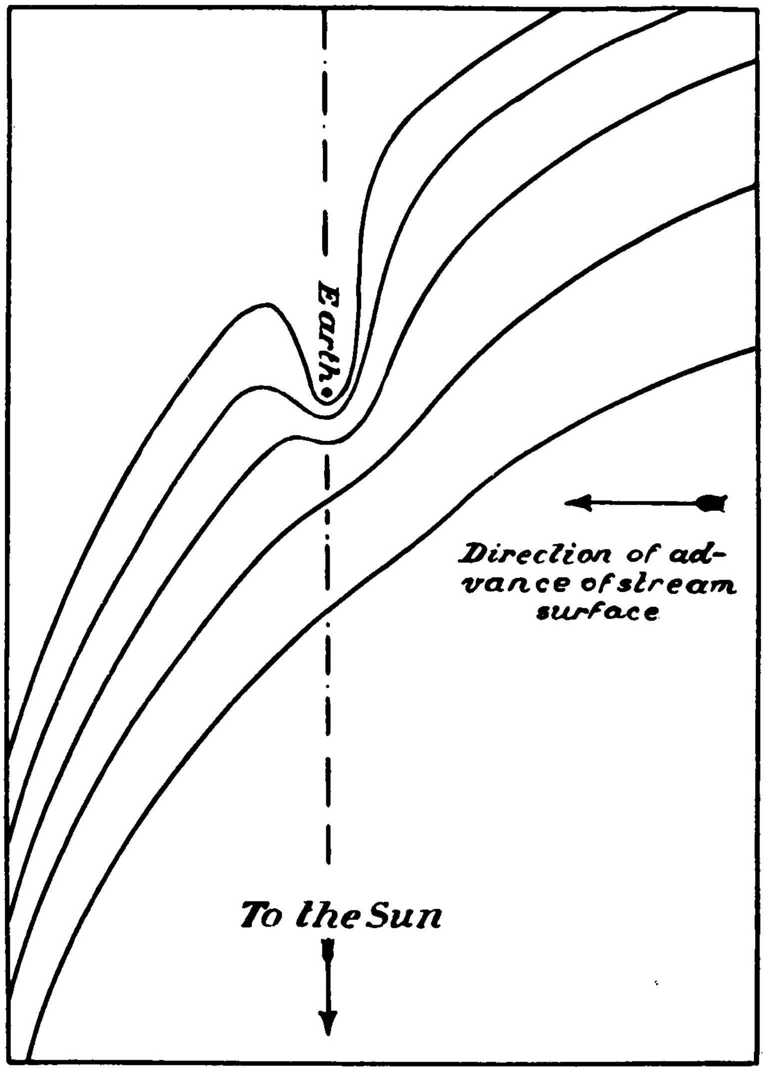

Fig.1--Successive equatorial sections of the surface of advancing stream

(after Chapman and Ferraro)

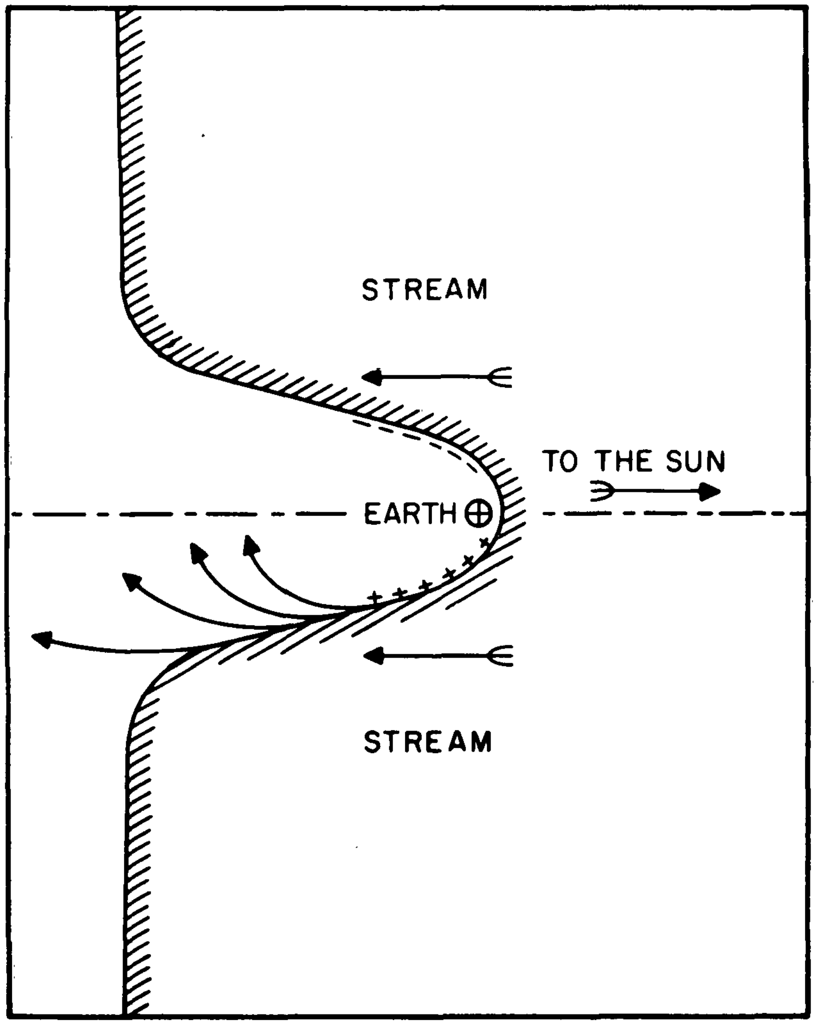

Fig.2--Equitorial section of magnetospheric boundary (after Chapman and Ferraro)

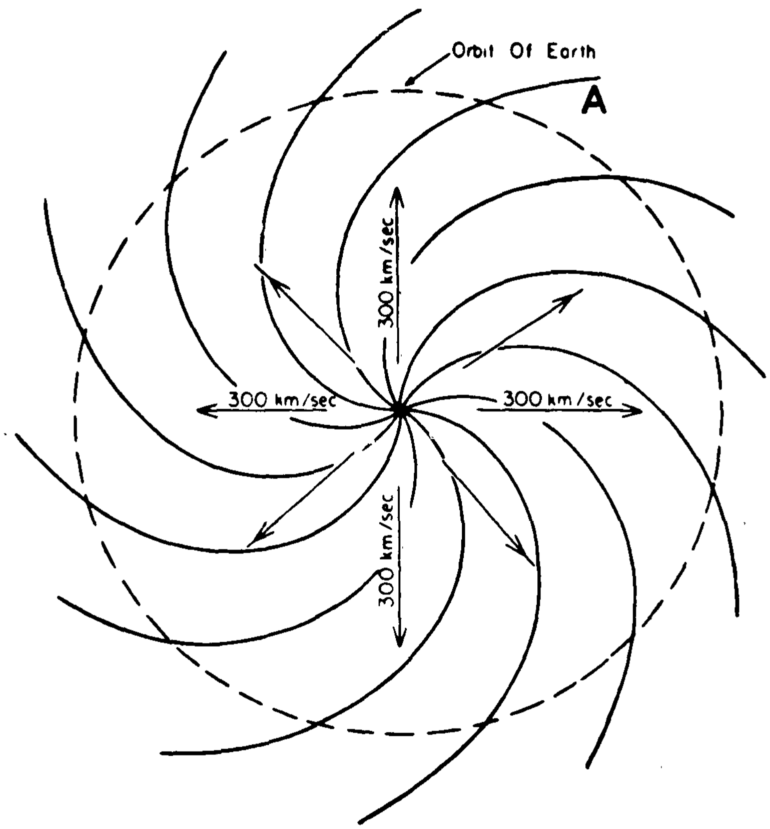

Fig.3--Extension of the general solar field by an idealized uniform quiet-day solar wind of 300 km/sec in the solar equatorial plane

(after Parker)

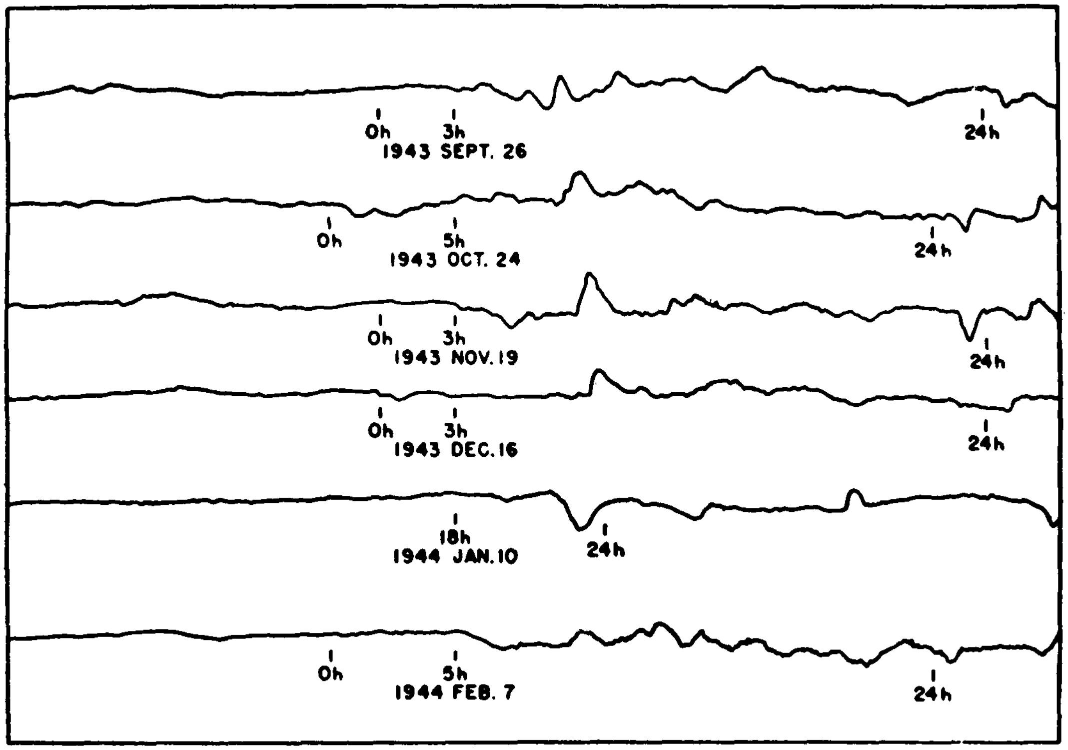

Fig.4--Tracings from the records of the horizontal component of the earth's magnetic field recorded at Mount Wilson, showing portions at the time of six abrupt onsets

(after Wulf and Nicholson)

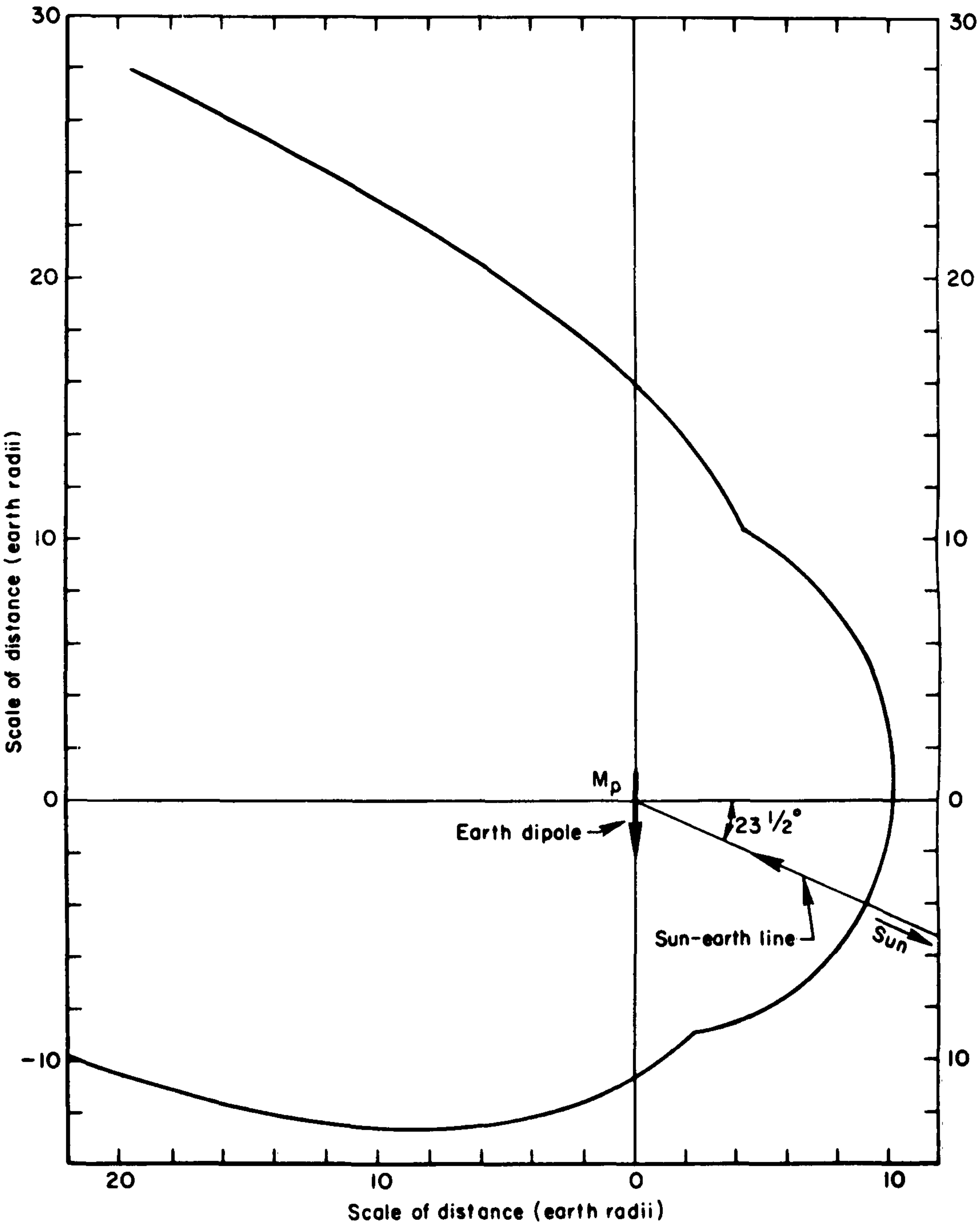

Fig.5--Form of boundary of magnetosphere in the meridian plane containing dipole axis and sun-earth line, winter solstice

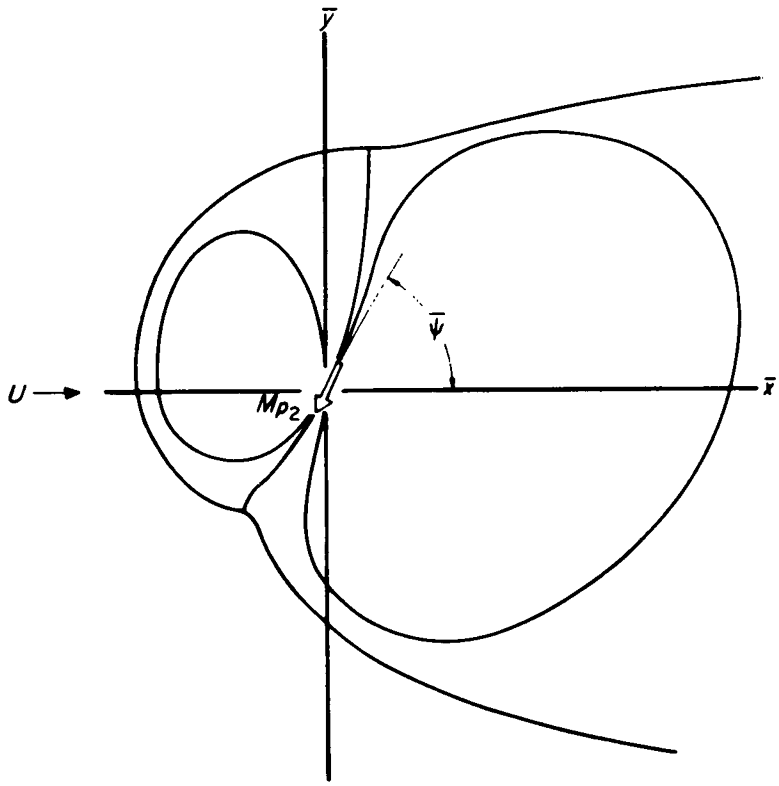

Fig.6--Magnetospheric boundary

(after Zhigulev and Romishevskii)

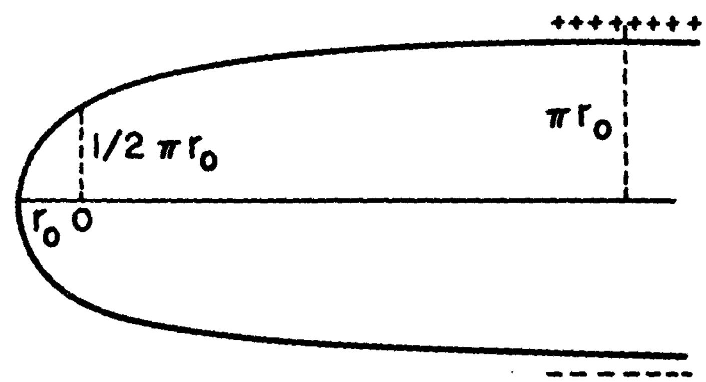

Fig.7--Approximate magnetospheric boundary
(after Ferraro)

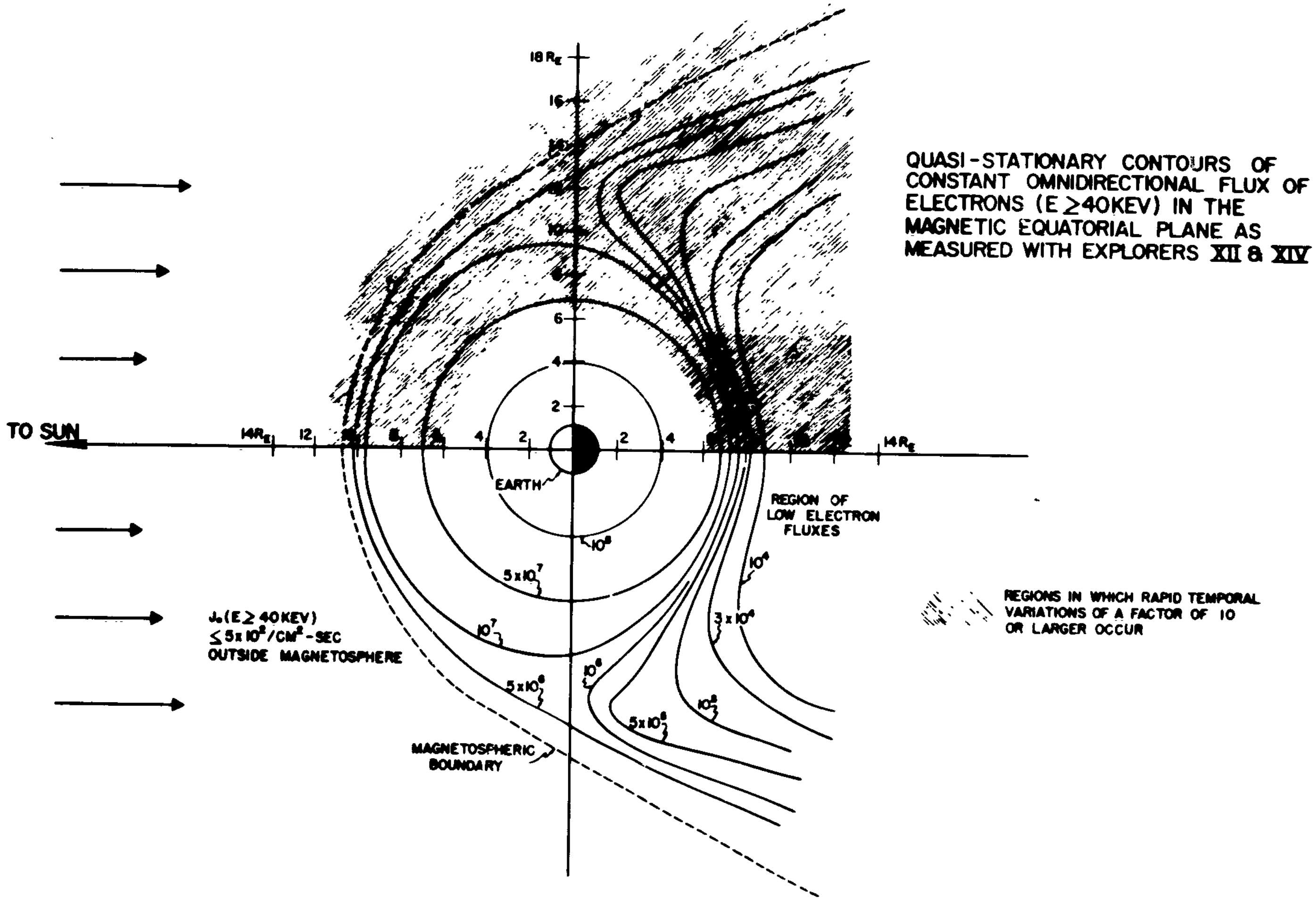

Fig.8--Quasi-stationary contours of constant omnidirectional flux of electrons (E ≥ 40 Kev) in the magnetic equatorial plane as measured with Explorers XII and XIV

(after Frank, Van Allen, and Macagno)

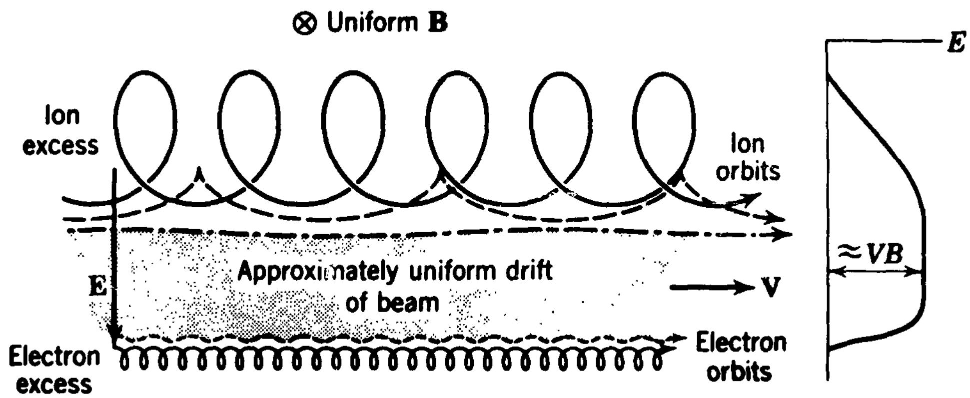

Fig. 9--Schematic representation of typical particle orbits and magnitude of electric field in a dense beam of ions and electrons crossing a magnetic induction B. The beam is assumed to be thick in the B-direction.

(after Rose and Clark)

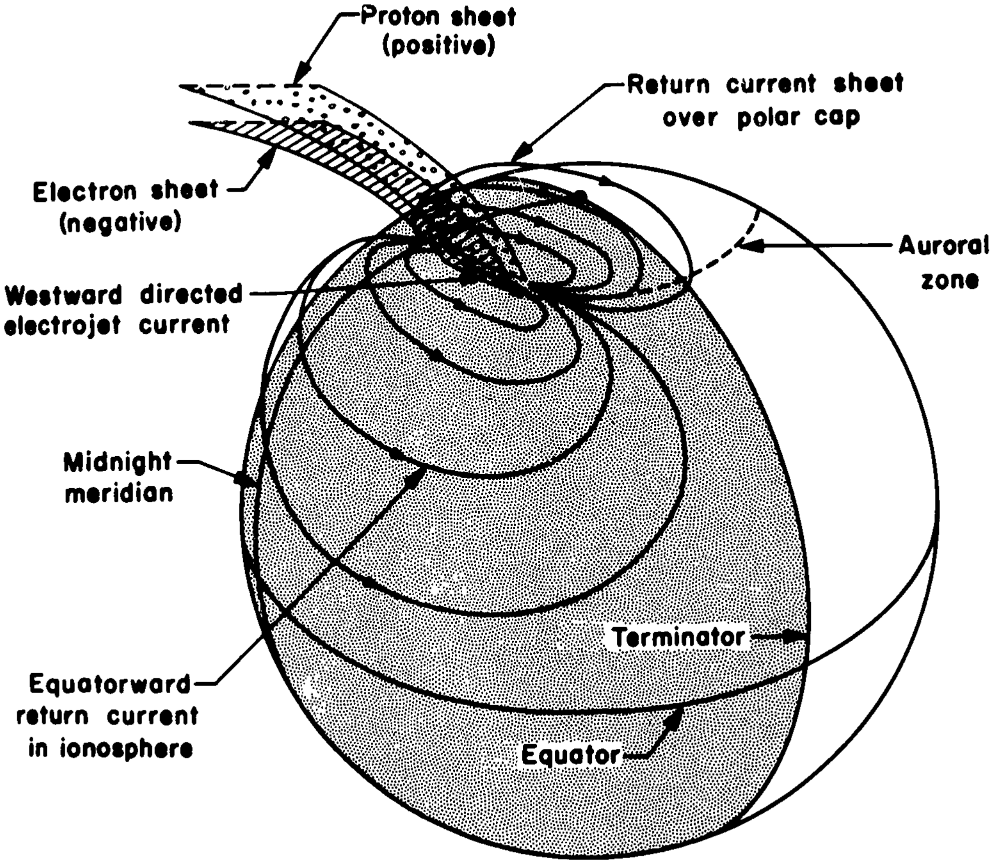

Fig.10--Polarization of radiation incident in the auroral zone and Hall conduction polar-electrojet currents

(after Kern)

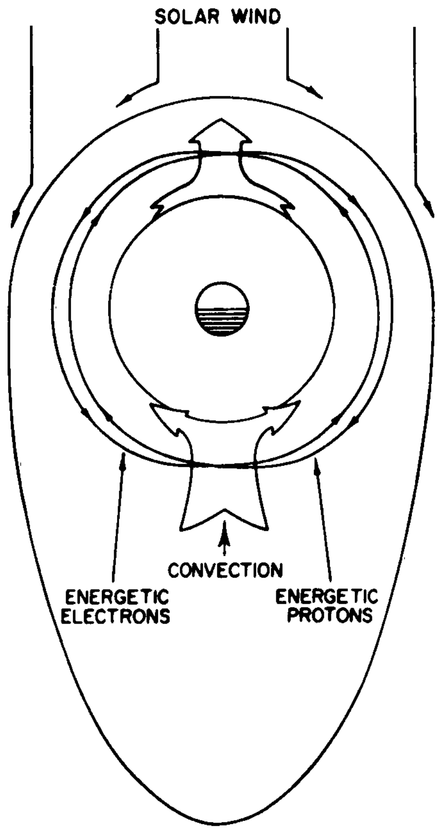

Fig.11--Theoretical circulation of the magnetosphere (after Axford and Hines)

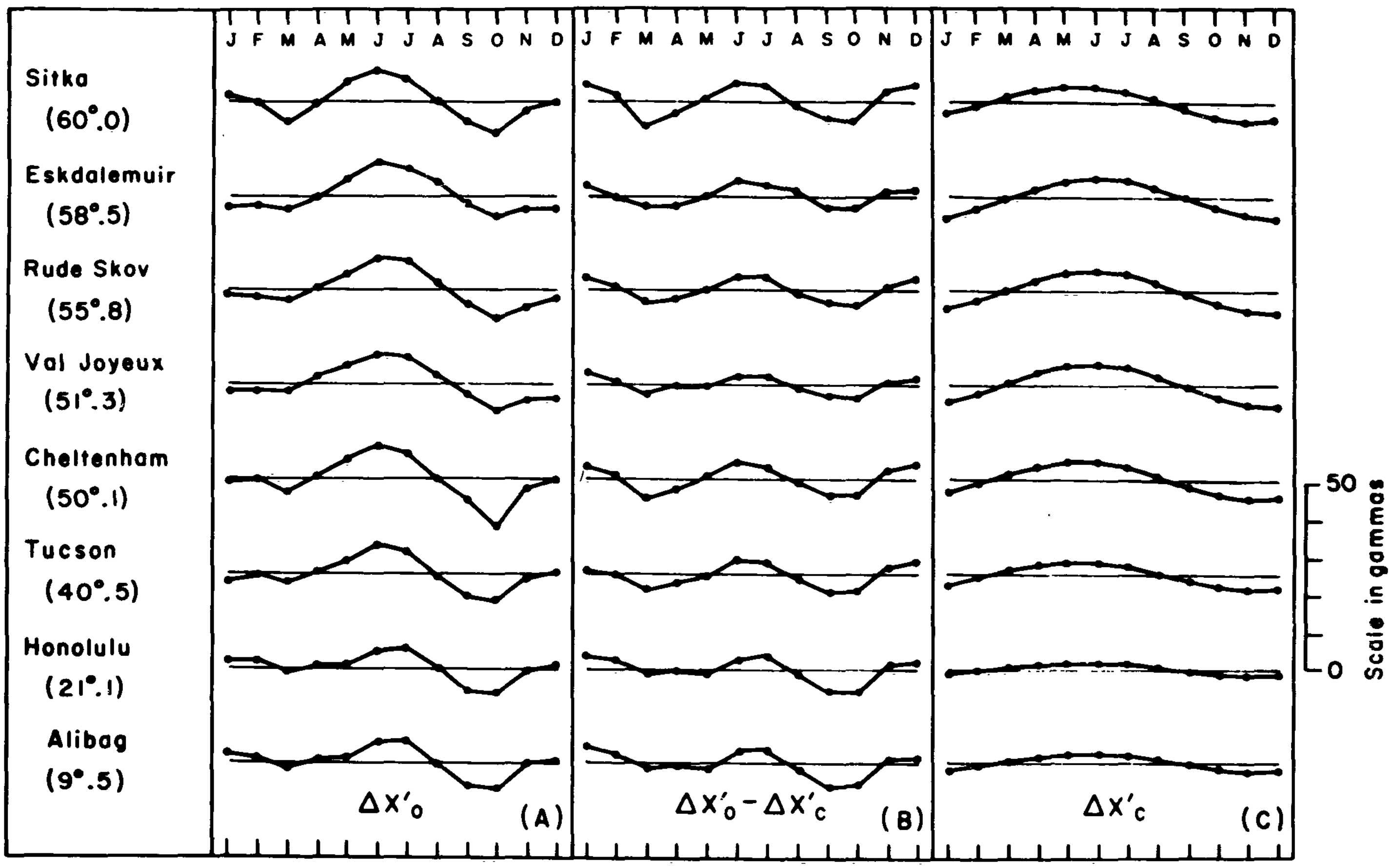

Fig.12--Average annual variation of X'-component, 1911 to 1935

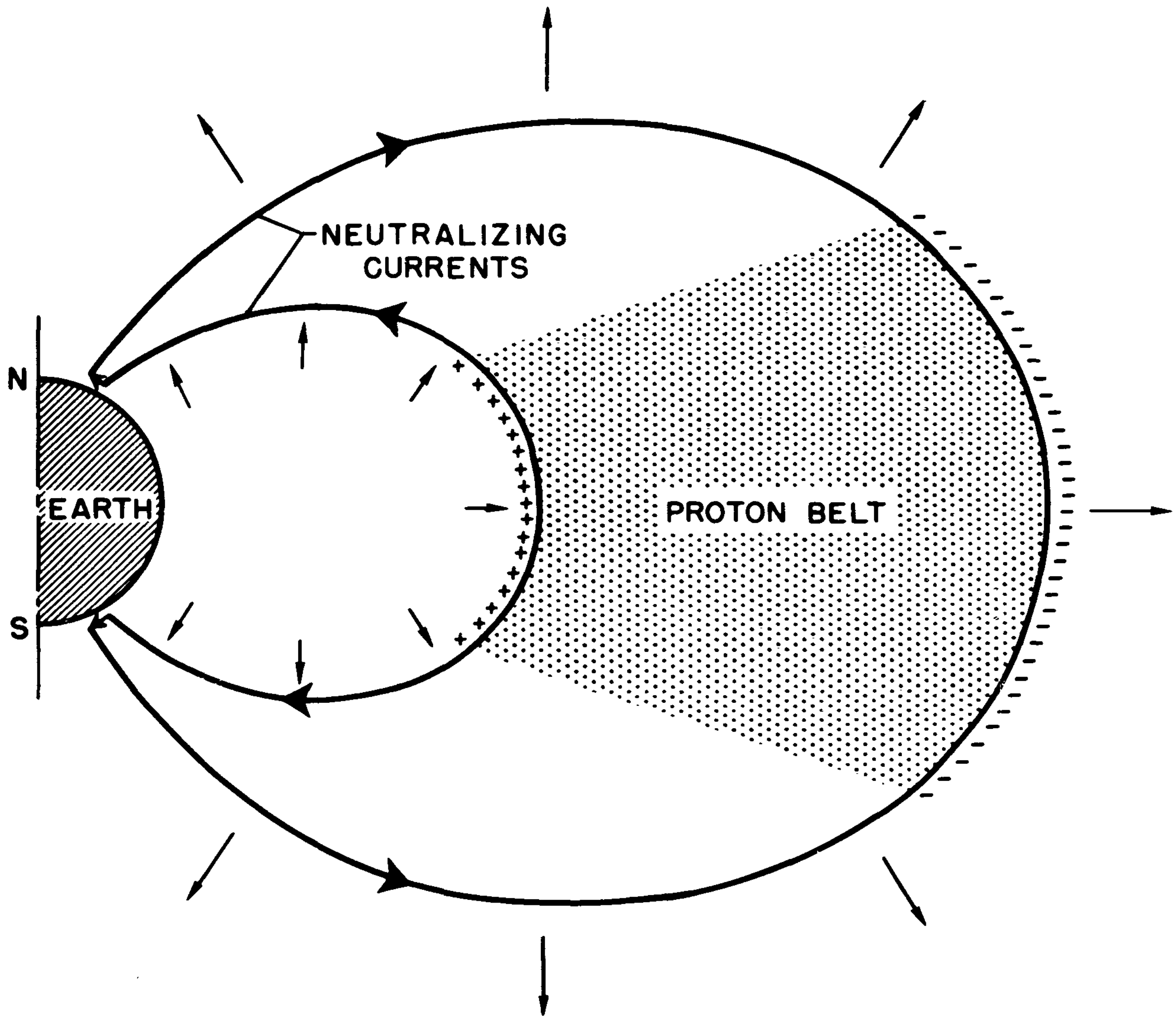

Fig.13--Current and electric fields in magnetosphere during magnetic bay (after Fejer)

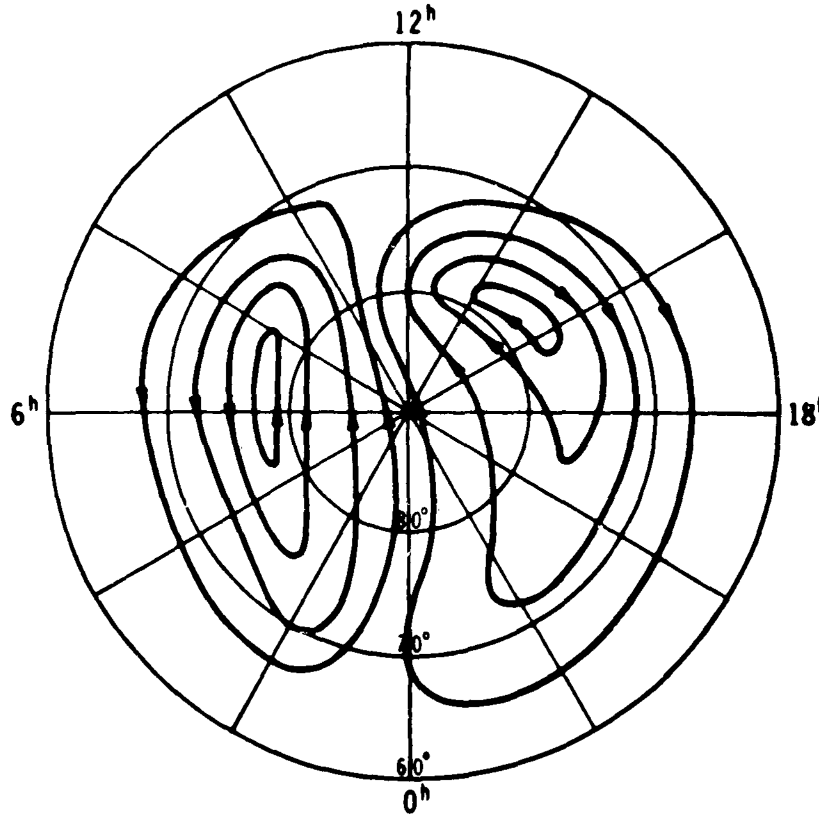

Fig.14--The additional sunlit polar cap current pattern. Sq(SP) (Electric current between adjacent lines is 2 x 10^4 amp)

(after Nagata)

1920

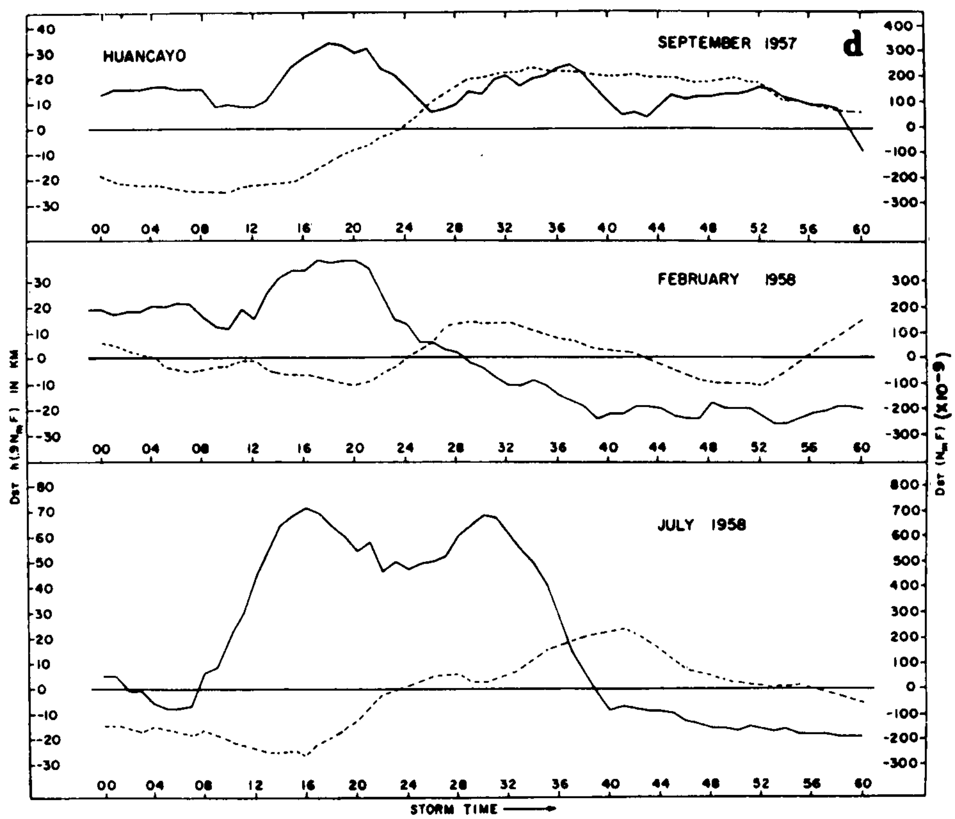

Fig.15--Dst variations of the maximum electron density of the f region (broken line) and the h(0.9N_mF) during storms

(after Somayajulu)

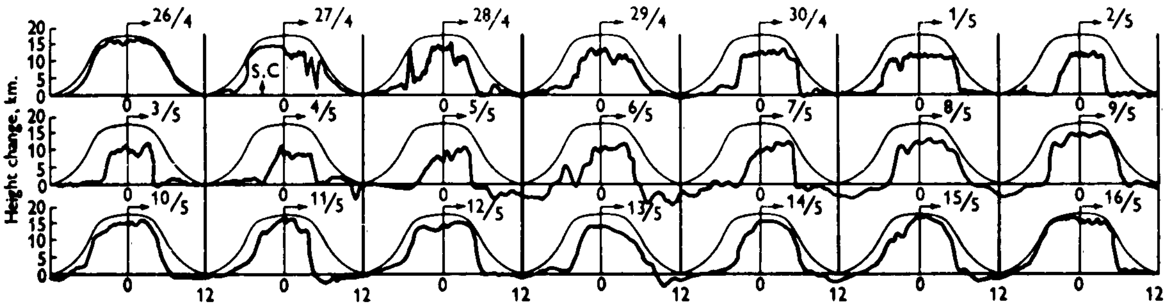

Fig.16--Variations in phase height of waves of frequency 16 kc/sec. Observed at Cambridge, 1956

(after Ratcliffe and Weekes)

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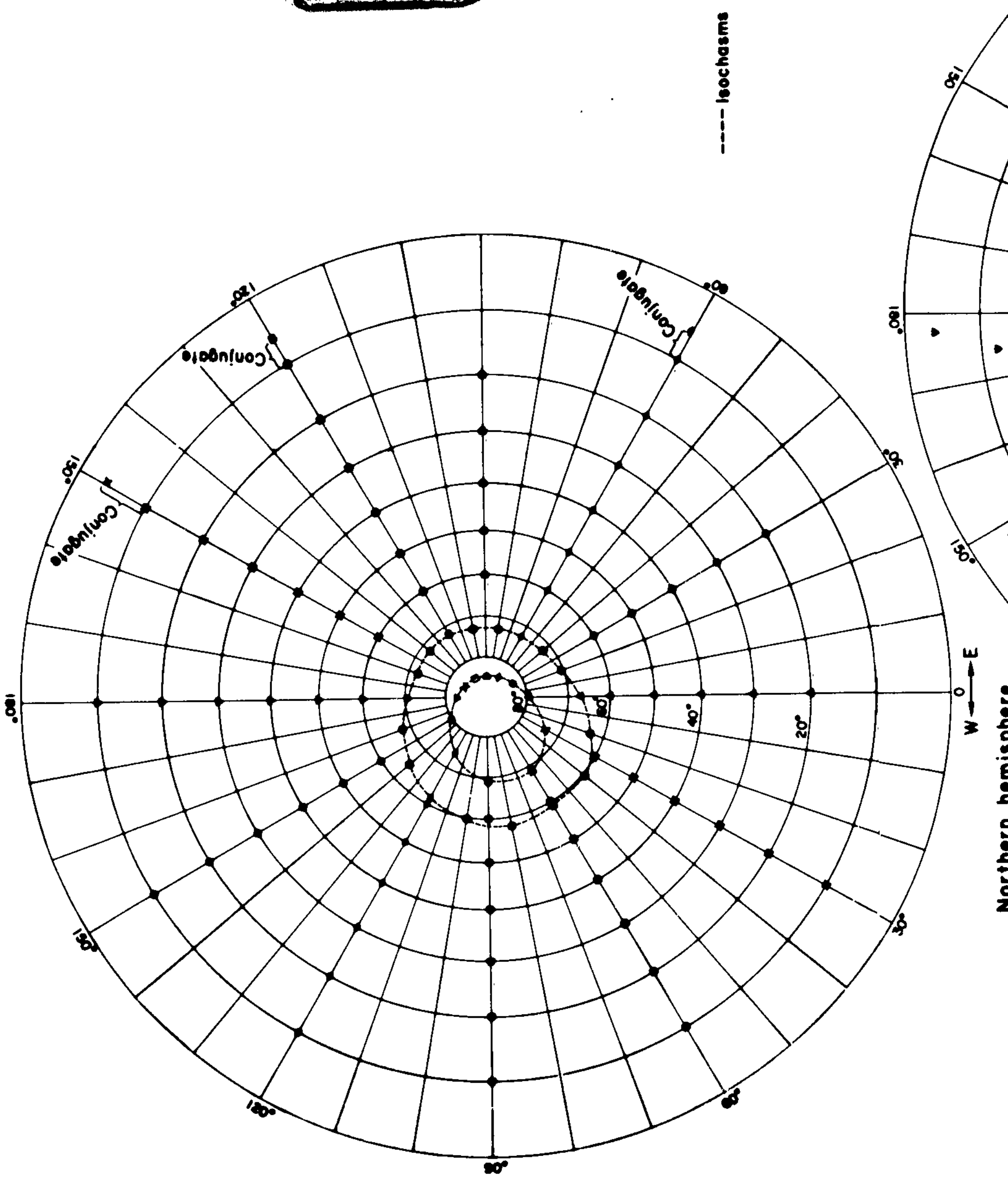
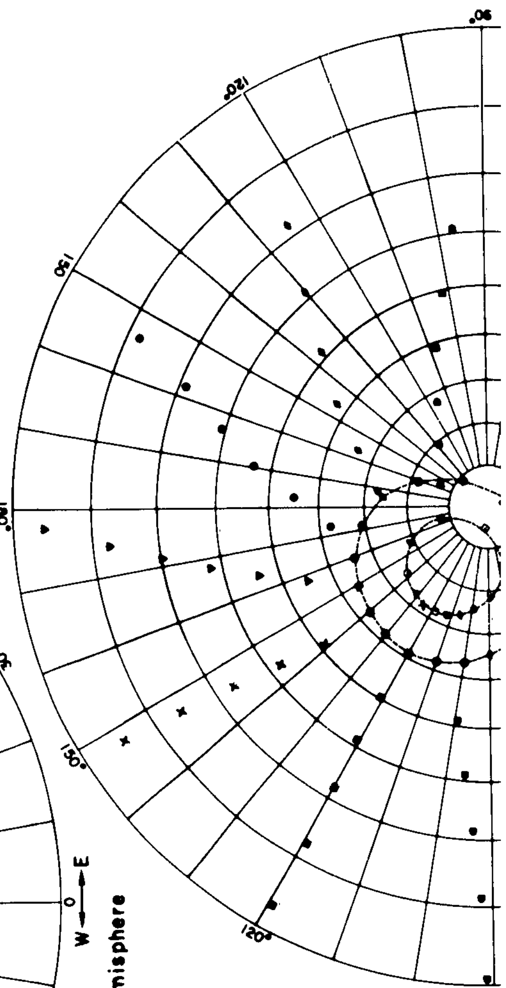
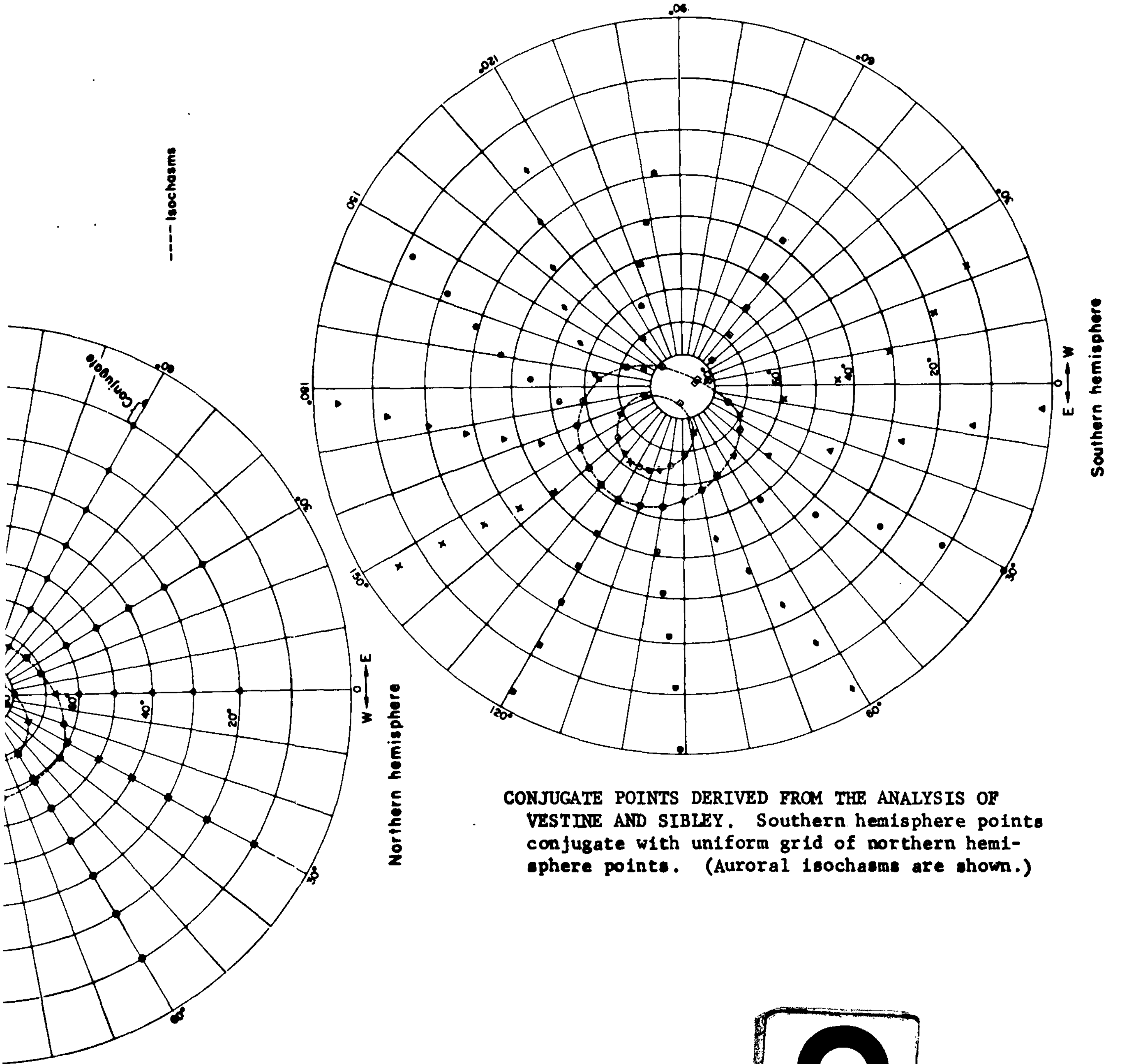
APPENDIX





CONJUGATE POINTS
VESTINE AND SIB
conjugate with
sphere points.



CONJUGATE POINTS DERIVED FROM THE ANALYSIS OF VESTINE AND SIBLEY. Southern hemisphere points conjugate with uniform grid of northern hemisphere points. (Auroral isochasms are shown.)

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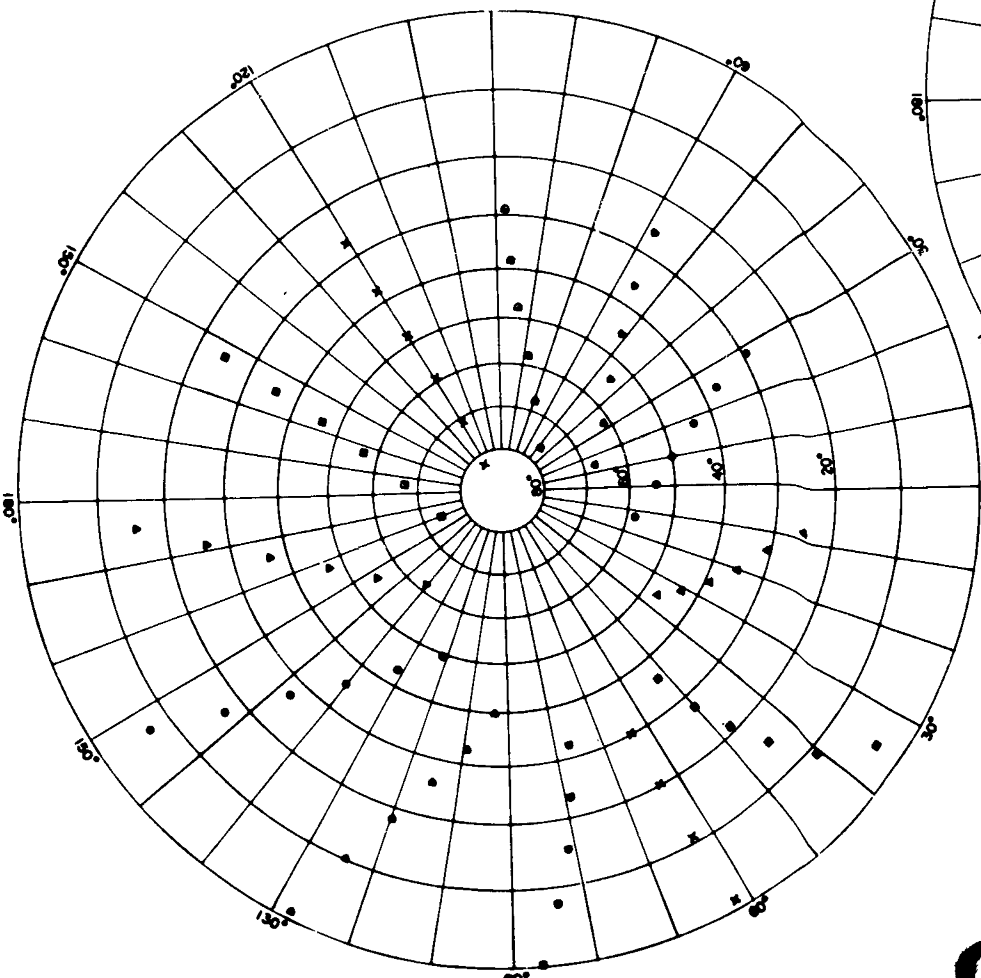

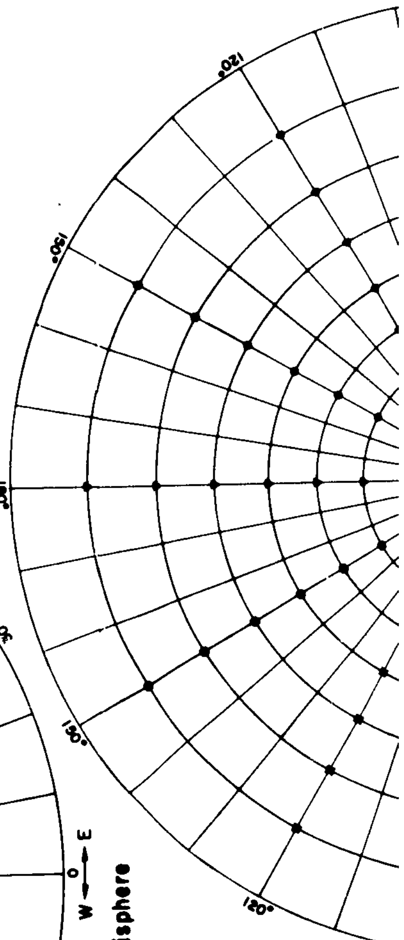

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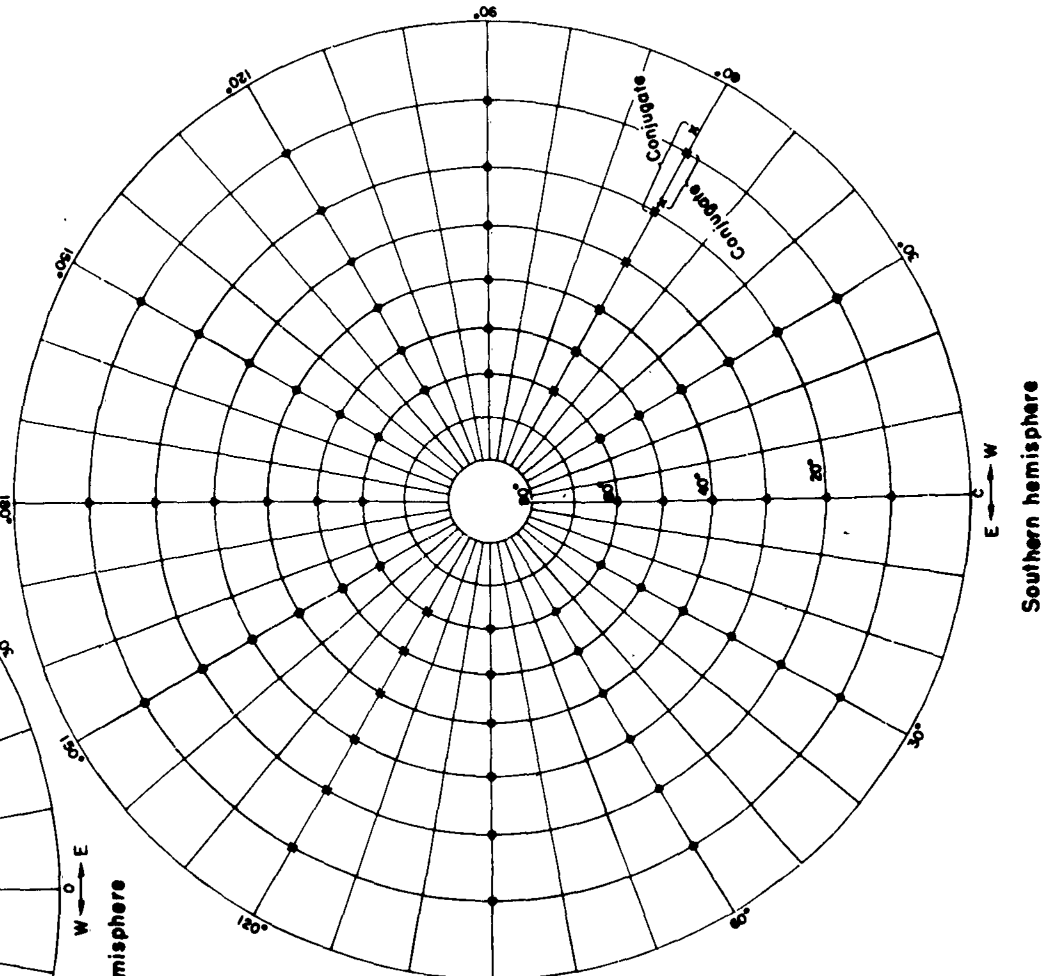

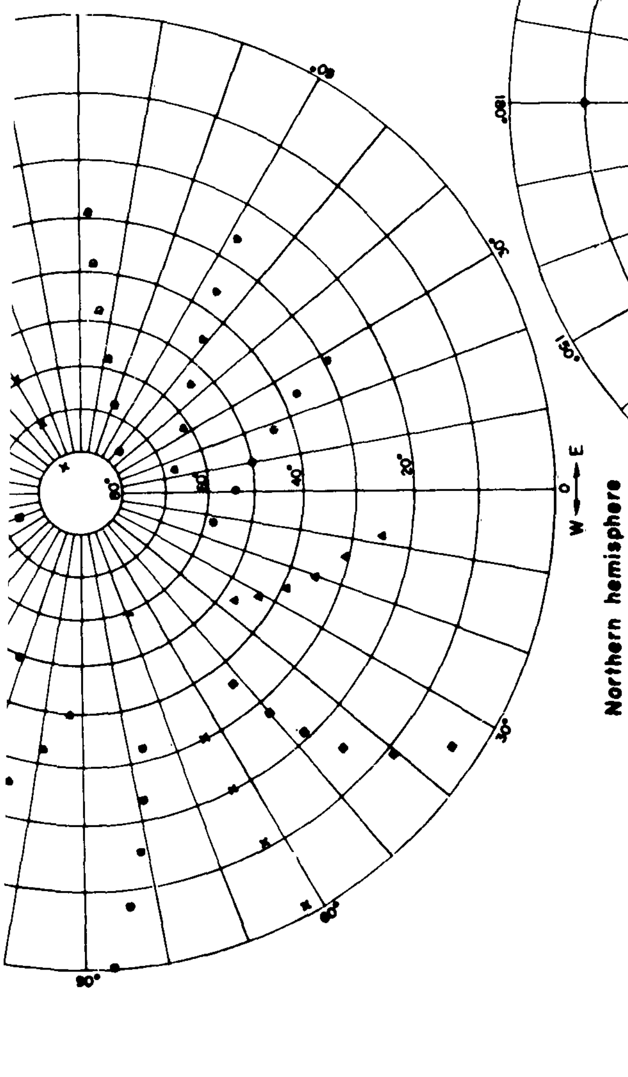

CONJUGATE POINTS DERIVED FROM THE ANALYSIS OF VESTINE AND SIBLEY. Northern hemisphere points conjugate with uniform grid of southern hemisphere points.

2